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Scanned and spot measured canopy temperatures of cotton and corn

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Abstract

Canopy temperature is a useful indicator of crop water stress and can also be used for making timely irrigation scheduling decisions for center pivot and subsurface drip irrigation systems. However, it is not known how closely the measured canopy temperature from a circular area of the canopy surface compares with a larger continuous area that includes the full canopy width. A study was conducted in 2001 where canopy temperatures were measured with infrared thermocouples (IT) and a thermal scanner (TS) in field plots irrigated by surface drip irrigation using cotton (*Gossypium hirsutum* L.) and corn (*Zea maize* L.). Two water levels included full evapotranspiration replacement (high water, HW) in cotton and corn and a second water level in cotton (low water, LW), which received 50% of the HW cotton amount. The purpose of the study was to compare canopy temperature measured from a small canopy area using IT with that obtained from a larger area with a TS. Canopy temperatures in the HW cotton, and HW corn were measured on 8 days during a 20-day period that started at first bloom in cotton and the V14 growth stage of corn, including four successive days during one irrigation cycle. Differences in canopy temperature measured by the two sensors averaged 0.2 °C in HW cotton, 3.2 °C in LW cotton, and 0.6 °C in HW corn. When leaf cover within the canopy was sufficient to mask the soil background, canopy temperatures measured from a small area by IT were comparable to those from a larger area sensed by a TS.
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Keywords: Canopy temperature; Cotton; Corn; Infrared thermocouple; Thermal image

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1. Introduction

The early results with infrared thermometers caused scientists to recognize that a direct measurement of some plant parameter would be superior to measuring soil water status as an indicator of plant response to its edaphic and atmospheric environment (Jackson, 1982). Wiegand and Namken (1996) observed that individual cotton leaf temperatures increased with insolation and decreased with increasing turgor of leaves. Based on these observations a measurement protocol was developed and is currently used for making leaf temperature measurements during early afternoon. Later as infrared thermometers were commercially developed research moved from measuring single leaves to measuring canopy temperature.

Water stress indices were developed that incorporated the temperature of canopies. Examples of some complex stress indices are the Crop Water Stress Index (Jackson et al., 1981; Idso, 1982) and the Thermal Kinetic Window (Burke et al., 1988). Besides providing a quantification of water stress temperature indices are used to schedule irrigation. Infrared thermometers provide an accurate measurement of the area observed but these areas are small compared to those that can be measured with thermal scanners (TS). Infrared thermometers are preferred sensors for measuring plant temperature in individual fields or sub-areas of fields because of their lower cost and greater portability than thermal scanners. Infrared thermometers are used as hand-held sensors or mounted on different platforms to provide continuous measurement of temperature.

Individual infrared thermocouples (IT) can be mounted in fixed positions in a field or attached to mobile irrigation systems. An array of IT was mounted and aimed 45° downward and across rows on a center pivot irrigation system to examine the spatial variation in water stress of corn under different irrigation treatments in a highly variable field (Sadler et al., 2002). In another study, wheat canopy temperatures were measured with a portable IT that viewed the top surface of canopies at an angle of 35–45° from horizontal (Yuan et al., 2003). We have used individual IT mounted on a fixed pole in subsurface irrigation systems to measure cotton and corn canopies for the purpose of timing irrigation applications with the BIOTIC irrigation protocol (Upchurch et al., 1996; Wanjura and Upchurch, 1994; Wanjura and Mahan, 1994) The IT in cotton are mounted to provide a nadir view directly over the row viewing a circular area that is about 75% of the canopy width while those viewing corn are located above the canopy and oriented at a 45° horizontal angle across rows. The area viewed in cotton ranged from a circular diameter of 10 cm early in the growing season to 30–46 cm when maximum vegetative growth is attained. Continuous monitoring of crop temperature is performed by remote sensing using infrared thermal sensors positioned to observe a small area of the upper canopy surface exposed to sunlight (Wanjura and Upchurch, 2000).

Thermal imaging has been used to measure field crop temperatures for many years. A study by Bartholic et al. (1972) used an airplane mounted thermal scanner to measure irradiance in the 8–14 μm wavelength interval. From measurements of cotton plots with a wide range of water stress, they concluded that infrared imagery had potential for distinguishing water-stressed and nonstressed fields in addition to evaluating uniformity of irrigation. A review of image-based remote sensing by Moran et al. (1997) addressed the potential of image-based remote sensing for providing spatially and temporally distributed information for precision crop management. Current limitations of image-based remote sensing applications include sensor attributes, such as restricted spectral range, coarse spatial resolution, slow turnaround time, and inadequate repeat coverage.

While the infrared sensing of temperature of a small area of canopy provides an accurate temperature for the area observed, the question arises about how representative is this measurement of a larger area of the canopy measured with a thermal imaging sensor. Obviously one factor that affects this question is the precision of measurement of the two different sensors and the spatial variability of canopy temperature in a field. Infrared thermocouples used in this study respond to radiation between 6.5 and 14 μm. Their accuracy varied with the deviation of the target temperature from the calibrated temperature of the infrared thermometer, i.e. from ± 2 °C for a target deviation of ± 3 to ±5% at a deviation of ±12 °C. Thus, it is important to select an infrared thermocouple whose calibrated temperature is at or near the center of the range of temperatures being measured. Thermal scanners are calibrated across a wide temperature range, but when spectral response is measured in the 8–14 μm (longwave) region and "earth" temperatures (−20 to 50 °C) are measured, accuracy is about 0.5 °C.

Our research on quantifying crop water stress and the use of canopy temperature to develop irrigation signals has used infrared thermocouples. The question addressed in this study is how does the canopy temperature measured from a relatively small area of the canopy surface compare to that of a larger area measured by thermal scanning. The objective of this study was to compare canopy temperature in cotton and corn measured from a small canopy area by infrared thermocouples with that obtained from a larger area with thermal imaging.

2. Materials and methods

Cotton (Paymaster HS2326) and corn (Dekalb 626) were planted on 9 May 2001 (DOY 129) into the beds of rows oriented north to south and spaced at 1 m. Previous rain provided sufficient moisture for germination and emergence. Initial corn emergence began on 13 May (DOY 133) and for cotton on 14 May (DOY 134). After emergence the crops were irrigated by drip laterals placed on the surface of each bed.

A thermal scanner was mounted on a self-propelled telescoping boom adjustable to a maximum height of 12.2 m. Equipment for thermal imaging included the thermal scanner (Inframetrics, Model 600L), a TV with built-in VCR, and a portable generator. Measurements were taken over two irrigation levels of cotton and one irrigation level of corn. Plot size of each crop was 12 rows wide by 170 m long. At the beginning of the study, three locations were selected along the row length and marked with flags in order to return to the same row locations on each measurement date. At each location, one row sites were marked. The three locations were 25, 50, and 75 m from the south end of the field.

Thermal scans over one row viewed a 0.76 m row length which was obtained by positioning the TS 2.9 m above the ground surface from the outside of the plot. Thermal scans began at 1345 h and were usually completed within 1.5 h. Scans began with the high water (HW) cotton which was irrigated to replace approximately 100% of potential evapotranspiration (PET), followed by low water (LW) cotton which received 50% of PET, and then irrigated corn which also received 100% of PET. If clouds covered the sun, we delayed for 2 min after the cloud cleared the sun before taking another scan.

2.1. Thermal image analysis

After completing the field thermal scan measurements, the VCR was connected to the USB port on a PC and the video images were reviewed. Images were selected from each location of each crop and were copied and stored in JPEG format. The JPEG images were later opened in Adobe Photo Shop software and converted to a gray scale of 0–255 luminosity with 0 being black and 255 being white. The range of temperatures represented in each grey scale (GS) image was stamped by the TS. A 10 °C range was sufficient to include all temperatures in most images. The image was opened and cropped to remove extraneous portions, leaving the canopy and furrows on each side of the single rows. The Rectangular Marquee Tool was used to select the single row canopies in the image with a minimum of bare soil included. A histogram was then generated and the statistics of the histogram were recorded, i.e. mean, standard deviation and median of luminosity, and number of pixels in the canopy image.

Later thermal maps were developed from the GS images to produce color maps of the canopy surface in 1 °C intervals. The canopy surface was selected by tracing the perimeter of the canopy, omitting shaded and sunlit soil outside the borders of the canopy using ERDAS Imagine (ERDAS Inc.) software. This perimeter canopy image was processed to create a raster file containing x, y, and z (grey scale) values. The raster file was analyzed in XCEL (Microsoft Corp.) to produce a frequency distribution of canopy temperature. The same raster file was then processed through SURFER 7 (Golden Software Inc.) to create color thermal maps (CTM) of the canopy surface. All color maps were normalized to the same temperature range and divided into 10 equal temperature intervals. These CTM were examined for temperature patterns of surface canopy temperature on different dates in the two water levels of cotton and one water level of corn.

2.2. IRT temperature

In each water level of cotton two infrared thermocouples (Model IRt/c. 2 G-K-80F/20C, EXERGEN Corporation) were positioned directly above the row at a height to provide a nadir view of adjacent row canopies near the location of the thermal scan readings nearest to the south end of each plot. The height of the infrared thermometer was changed as the cotton canopy size increased to view the top of the canopy without viewing bare soil. Corn had IT positioned above and viewed from a 45° vertical angle across rows. The 45° angle targeted the upper portion of corn leaves and reduced the amount of shaded leaf surfaces viewed below the top of the canopy. The canopy temperatures were saved as 15 min averages in a Campbell Scientific CR7 data logger. The thermal scanned canopy temperature was compared with the IT temperature that included the scanned time of measurement.

The horizontal positions of upper canopy leaves and their leaf angles were measured on two dates. Biomass estimates were made by sampling five representative plants in the vicinity of each location on each date of thermal scanning. Midday leaf water potential

(LWP) was measured along with thermal scanning by sampling three leaves at each field location with a portable pressure chamber.

2.3. Growth stages and dates

Thermal scans of HW level cotton and corn canopies were taken from a nadir viewpoint on 8 days between first bloom (DOY 183) and mid-bloom stage for cotton (Mauney and Stewart, 1986) and between the V14 and R3 growth stages of corn (Ritchie et al., 1997) on (DOY 205). Four of these scans were made on successive days of one irrigation cycle beginning with the day when irrigation was applied on DOY 199 and ending on DOY 202, the last day before the next irrigation application. Thermal scans during the irrigation cycle were made over all treatments.

3. Results and discussion

3.1. Leaf orientation

Leaf orientation of the upper-most five leaves of cotton and corn plants were measured as azimuth and vertical leaf angles on two dates (Table 1). Leaf shape, their distribution around the mainstem, and vertical orientation differed between the crops. The average leaf azimuth angle for both crops was ∼180° on both dates indicating that the distribution of the top five leaves was uniform about the mainstem in the horizontal plane. The azimuth angles of vertically adjacent leaves varied indicating that their positions in the horizontal

Table 1
Leaf angles in the upper portion of well-watered cotton and corn canopies, 2001

Date crop	Leaf number below mainstem terminal					Average
	1	2	3	4	5	
Azimuth angle (°)[a]						
DOY 163						
Cotton	161	235	162	192	158	182
Corn	176	178	210	175	194	186
DOY 183						
Cotton	134	198	212	144	216	179
Corn	111	237	126	204	135	164
Vertical angle (°)[b]						
DOY 163						
Cotton	130	123	129	118	118	124
Corn	18	22	23	30	38	26
DOY 183						
Cotton	110	113	111	119	113	111
Corn	17	23	27	31	39	35

[a] Azimuth angles were measured in the horizontal plane in a clockwise direction from north.
[b] Vertical angles were measured between a vertical line and the surface of the leaf blade.

plane were also different. On both measurement dates vertical angle of cotton was 20–30° below the horizontal plane in contrast to corn leaves which were 60° above the horizontal plane.

The differences in vertical leaf angles between the two crops contribute to the differences in their canopy architectures. Cotton canopies are compact with horizontally positioned broad leaves and when viewed from nadir present a relatively continuous sunlite upper surface with few shaded leaf areas visible below the surface. Corn canopies are less compact with vertically positioned elongated leaves and when viewed from nadir have an irregular sunlite upper surface with numerous shaded areas. The canopy surface of corn appears to have a more irregular shape than cotton which may also affect its temperature variability. By positioning an IT above the canopy and changing the viewing angle to 45° more sunlite leaves and less shaded leaf area in corn can be observed.

3.2. Biomass

Plants were harvested on four dates during the period of thermal scanning, and plant height and leaf area data are summarized in Table 2. Plant populations for LW cotton, HW cotton, and corn were 138 000, 144 600, and 73 300 plants/ha, respectively. Plant leaf area and leaf area index values indicated the development and size of canopies. Between DOY 184 and DOY 206 for HW cotton and DOY 186 and DOY 206 for corn there was little change in canopy size. Leaf area per plant and leaf area index values on DOY 206 indicate that LW cotton canopies were about 50% smaller than those of HW cotton. The cotton began to set bolls on DOY 183. Corn began to tassel on DOY 186 and leaf area gradually declined afterwards as lower leaves dried and abscised. There was no significant difference due to location along the row for plant leaf area or leaf area index for corn or cotton. Thus, uniformity of water application by the surface drip irrigation system was assumed to be relatively high.

3.3. Leaf water potential

Midday leaf water potential values were different on each day during the period of one irrigation cycle from 18 to 21 July (Table 3). LWP values of corn were highest on each of the days during the irrigation cycle. Cotton had large negative LWP values for both irrigation levels during the irrigation cycle, even on the day that irrigation was applied. The irrigation well pump had experienced intermittent problems for several weeks that interfered with the normal irrigation cycle and quantities applied. Maximum air temperature of 40.6 °C also occurred during the days immediately before the beginning of the irrigation cycle. Midday LWP values for well watered cotton would normally be in the range of −1.5 to −1.8 MPa. Even so, these differences in LWP values for cotton in the two water levels resulted in different amounts of vegetative growth.

3.4. Infrared thermocouple and thermal scanner canopy temperatures

The IT were checked with a calibrated blackbody to insure measurement accuracy. Canopy temperatures were checked by plotting the diurnal set of 15 min temperatures of all

Table 2
Plant height, leaf area, and leaf area cotton and one water level of corn, 2001

Date crop	Location			Average
	1	2	3	
Plant height (cm)				
DOY 184				
HW cotton	60 a[a]	61 a	63 a	61
DOY 186				
Corn	186 ab	168 b	Corn	184
DOY 193				
Corn	200 a	191 a	193 a	195
HW cotton	61 b	71 a	75 a	69
DOY 206				
Corn	199 a	189 a	201 a	196
HW cotton	73 a	75 b	89 a	79
LW cotton	61 a	67 a	63 a	64
Plant leaf area (cm^2/plant)				
DOY 184				
HW cotton	1489 a	1683 a	1790 a	1654
DOY 186				
Corn	6128 a	5523 a	6418 a	6023
DOY 193				
Corn	5627 a	5403 a	5157 a	5396
HW cotton	1413 a	1233 a	1472 a	1373
DOY 206				
Corn	5335 a	4352 a	4713 a	4800
hw cotton	1689 a	1665 a	1690 a	1681
LW cotton	738 a	1059 a	925 a	907
Leaf area index				
DOY 184				
HW cotton	2.2 a	2.4 a	2.6 a	2.4
DOY 186				
Corn	4.5 a	4.1 a	4.7 a	4.4
DOY 193				
Corn	4.1 a	4.0 a	3.8 a	4.0
HW cotton	2.0 a	1.8 a	2.2 a	2.0
DOY 206				
Corn	3.9 a	3.2 a	3.5 a	3.5
HW cotton	2.4 a	2.4 a	2.4 a	2.4
LW cotton	1.0 a	1.5 a	1.3 a	1.3

[a] Values in the same row followed by different letters are statistically different at the 0.05 probability level according to Duncan's new multiple range test.

Table 3
Leaf water potential values during one irrigation cycle for two irrigation levels of cotton, and one water level of corn, 2001

Date	Time in irrigation cycle, day number[a]	Cotton		Corn
		HW	LW	HW
Leaf water potential (MPa)				
DOY 199	ID + 0	−2.33 b[b]	−3.05 a	−1.72 c
DOY 200	ID + 1	−2.60 b	−3.28 a	−2.06 c
DOY 201	ID + 2	−2.63 b	−3.23 a	−2.29 c
DOY 202	ID + 3	−3.11 b	−3.39 a	−2.18 c

[a] Time in irrigation cycle is designated by irrigation day (ID) plus the number of days from the day of irrigation application.

[b] Values in the same row followed by different letters are statistically different at the 0.01 probability level according to Duncan's new multiple range test.

treatments each day after IT were placed in the field plots. The canopy temperature curves of different irrigation levels were inspected to determine if predawn temperatures of all water levels were similar and that midday temperatures of HW irrigation treatments were lower than LW irrigation treatments. IT were either repositioned or replaced when the temperature conditions were not met. The IT canopy temperatures for DOY 199 shown in Fig. 1 are examples of correctly operating sensors since early morning canopy temperatures before

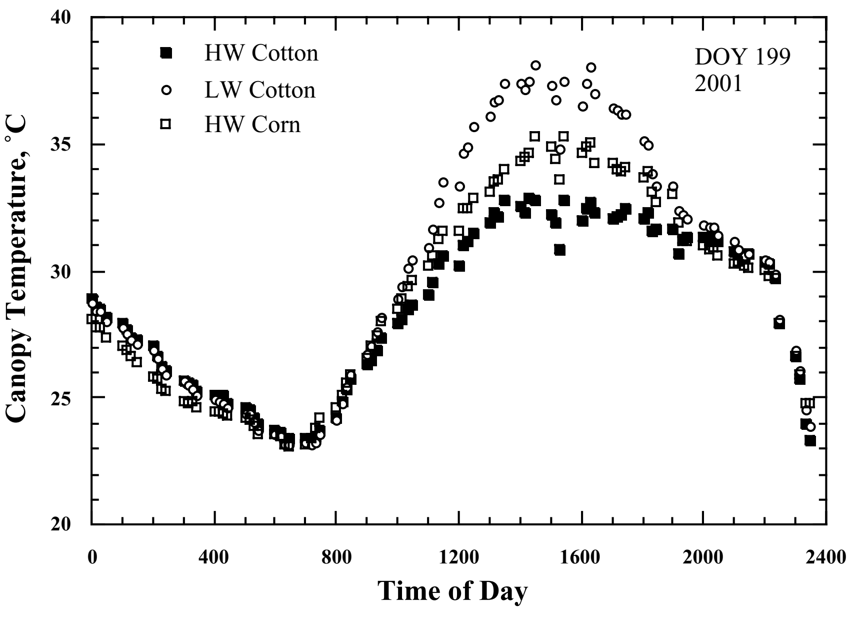

Fig. 1. Canopy temperatures measured with infrared thermocouples in the HW cotton, LW cotton, and HW corn appear to be operating correctly because predawn temperatures are similar and midday HW temperatures are lower than LW temperatures, 2001.

sunrise were similar in both water levels, but unalike during midday when differences in water stress were highest.

Canopy temperatures of the HW cotton were measured with infrared thermocouples and the TS on 8 days including 4 days during one irrigation cycle beginning on DOY 199, Fig. 2a and b. These temperatures were compared with those of LW cotton which were measured only during the one irrigation cycle. During the irrigation cycle (DOY 199–DOY 202) canopy temperature differences between the LW and HW levels were greater for measurements made with IT than those measured by the TS. The pattern of

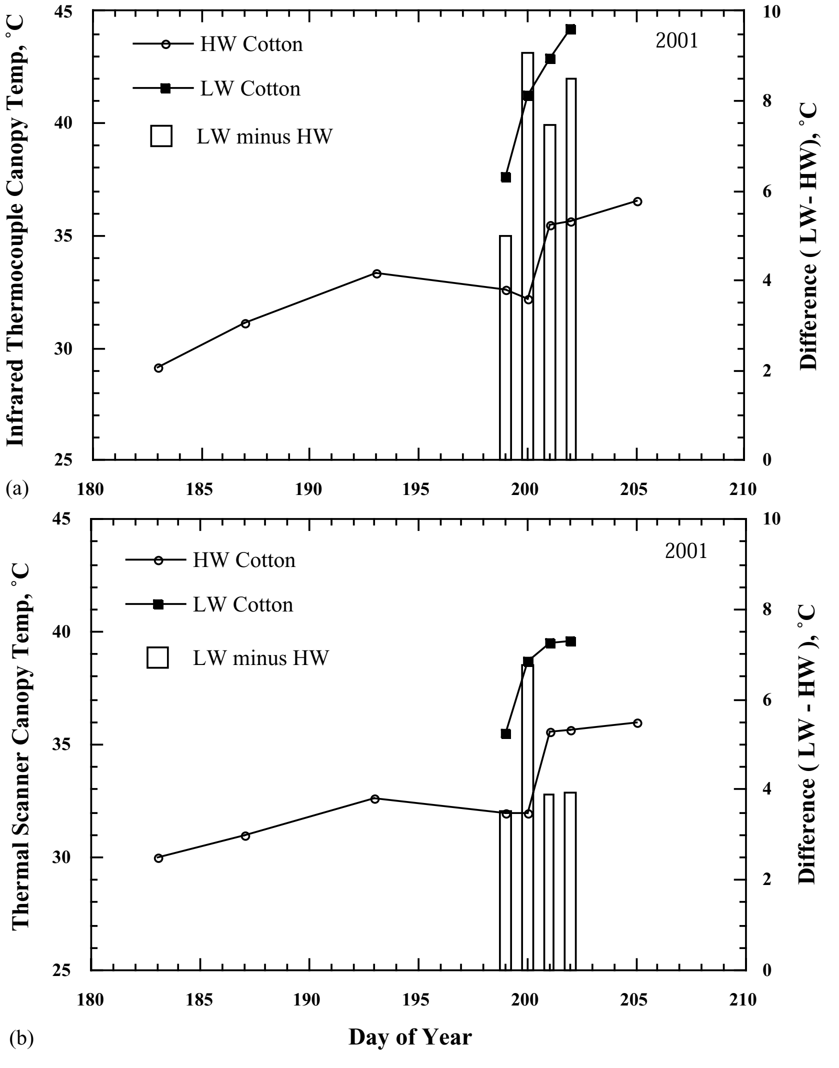

Fig. 2. Comparison of canopy temperature measured from two water levels of cotton with infrared thermocouple and thermal scanner sensors, 2001.

canopy temperature differences during the 4 days was similar for both types of sensors. The largest canopy temperature difference between the two water levels was 6.8 and 9.1 °C, respectively, for the TS and IT on DOY 200.

A comparison of canopy temperatures within each water level measured by the two thermal sensors is shown in Fig. 3a-c for cotton and corn. Cotton canopy temperatures measured by the sensors agreed more closely in the HW level than in the LW level. In the HW level, the largest temperature differences between the two sensors occurred on DOY 193 and DOY 199. These differences of 0.9 and 0.8 °C were slightly greater than the ∼0.5 °C measurement accuracy of the IT and TS. In LW cotton, temperature differences of the two sensors ranged from 2.1 to 4.6 °C during the 4-day period. Infrared thermocouple temperatures in the LW level were abnormally high probably due to observing some soil surface through the canopy. The differences in canopy temperature (IT–TS) measured by the two sensors were both positive and negative in HW cotton but always positive in LW cotton. During the 4 day irrigation cycle differences in temperature measured by the two sensors averaged 0.2 °C in the HW cotton level and 3.2 °C in the LW cotton level.

Canopy temperature differences of HW corn measured by the sensors agreed within 0.5 °C except on DOY 200 and DOY 205 when the differences were 1.4 and 1.5 °C. The differences in corn canopy temperature measured by the two sensors (IT–TS) were negative except on DOY 193 when temperatures were highest. During the irrigation cycle differences in corn temperature measured as (IT–TS) averaged −0.6 °C. Canopy temperatures measured by the TS in corn were higher than those measured by the IT, which was opposite of the temperatures measured in cotton. The relatively higher TS temperature of corn was not likely caused by the 45° angle of the IT since this angle should have increased the amount of top leaves and reduced the shaded leaves viewed and thus increase the temperature sensed by the IT. In both crops, the TS measurements were nadir views.

The cotton canopy temperatures measured by the IT and TS were linearly correlated in both water levels (Fig. 4). The linear regression coefficients were 1.43, 1.06, and 1.40 for LW cotton, HW cotton, and the combined water levels, respectively. In LW cotton, the infrared thermocouples were apparently viewing a higher percentage of leaves exposed to direct solar radiation than the TS which viewed portions of the canopy below the surface that were partially shaded and cooler. The canopy temperatures measured by the two sensors agreed most closely in HW cotton, as indicated by its regression coefficient that was closer to 1.0 than for the LW level. The linear regression coefficient of the temperatures measured by the two sensors in corn (1.04) was similar to that of the HW cotton (1.06). Both HW cotton and corn canopies were well-watered and had similar regression coefficients, which suggests that the proportion of sunlit leaves and shaded leaves of both crop canopies were more similar than the LW cotton which was more water-stressed and slightly wilted.

3.5. *Canopy imagery*

Nadir views of single-row cotton and corn canopies are shown in color and grey-scale thermal images for DOY 202 (Fig. 5). The color photos provide visual information for comparing the differences in canopy architecture between the two crops and the difference in canopy condition between the two water levels of cotton. The HW cotton canopy leaves

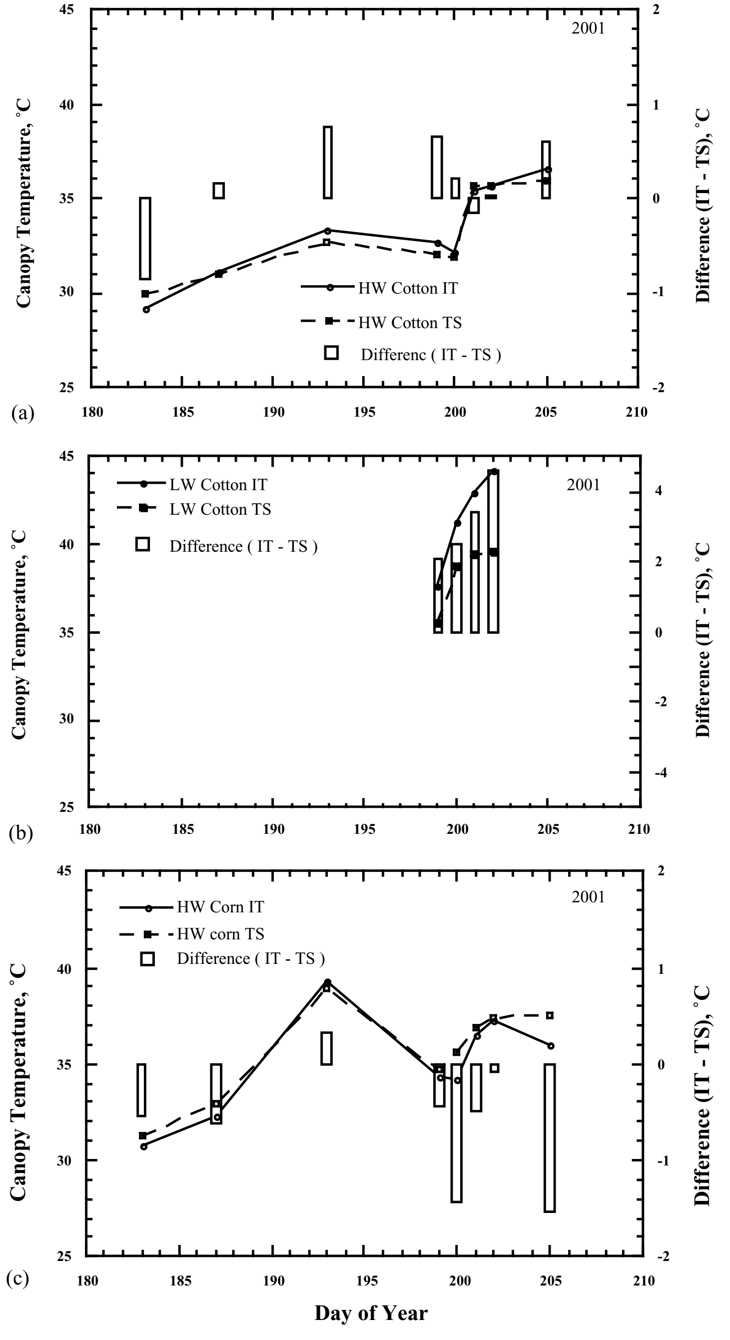

Fig. 3. Comparison of canopy temperatures measured by infrared thermocouples and a thermal scanner for HW cotton, LW cotton, and HW corn.

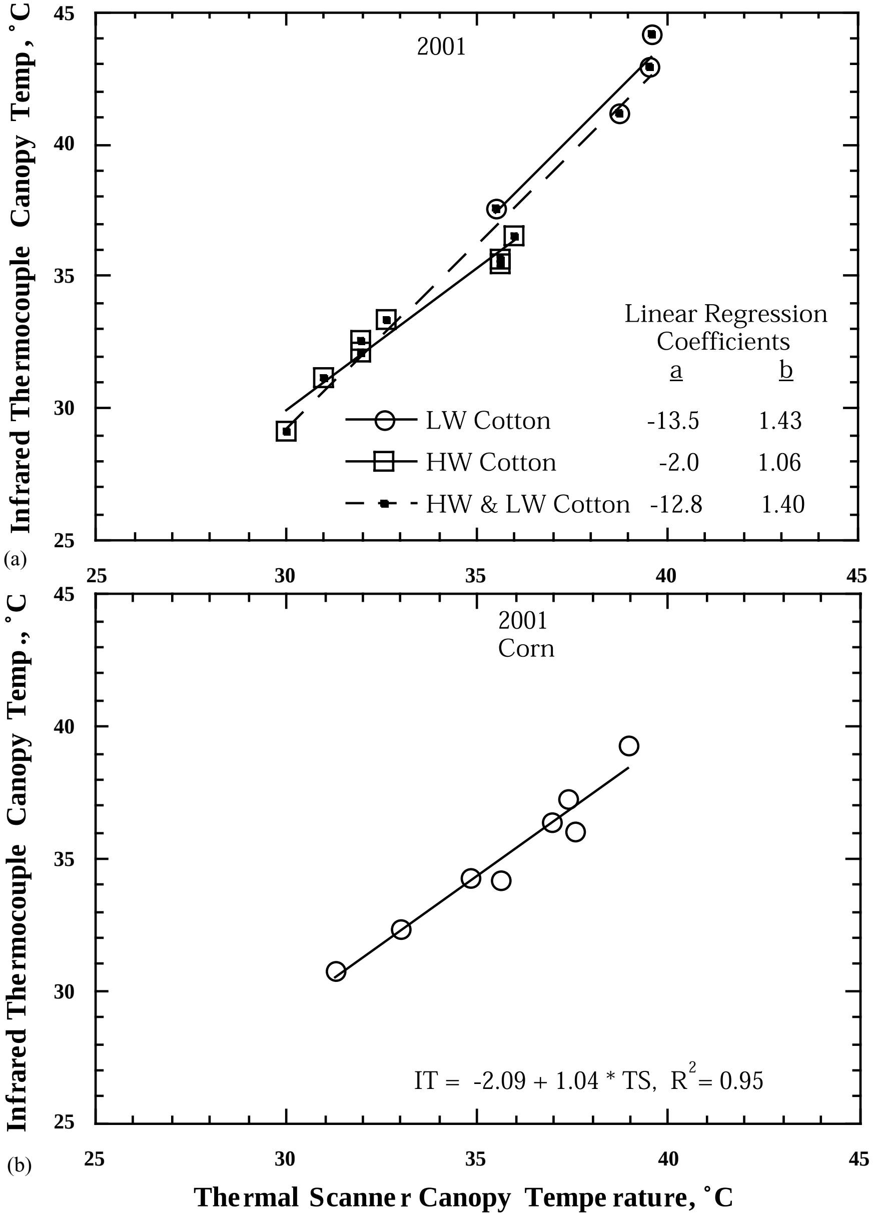

Fig. 4. Relationship between canopy temperature measured with a thermal scanner and infrared thermocouples for (a) HW cotton and LW cotton and (b) HW corn, 2001.

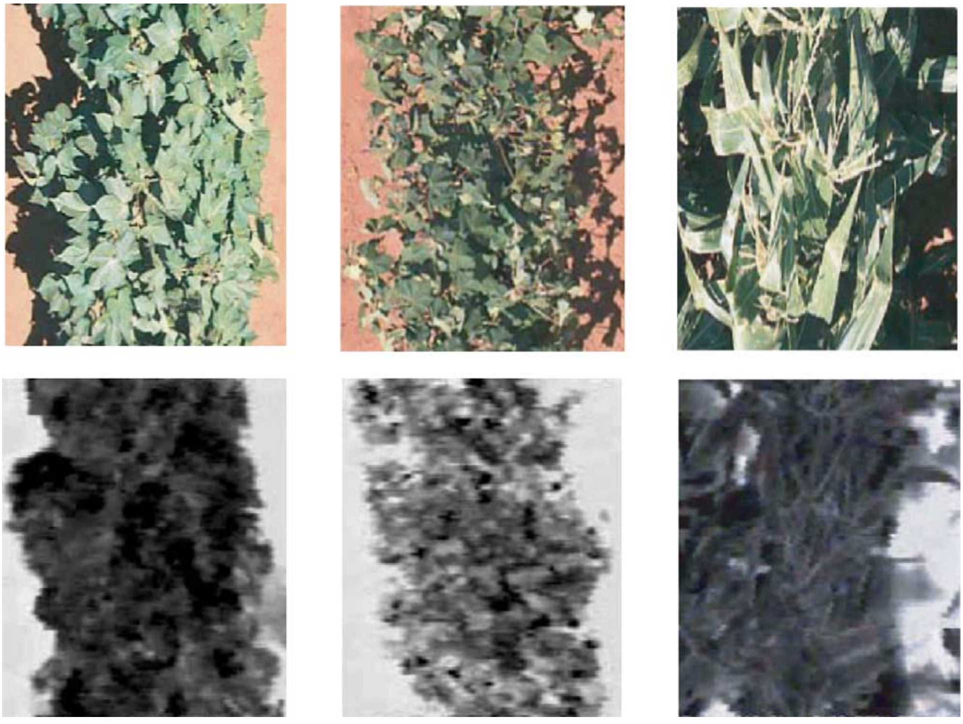

Fig. 5. Nadir view color photos and grey-scale thermal images of 0.8 m single row lengths of HW cotton, LW cotton, and HW corn on DOY 202, 2001.

are turgid and form a relatively uniform surface of mostly sunlit leaves with a few shaded areas below the top surface that appear dark within the boundary of the canopy. Some leaves in the LW cotton canopy appear darker green in color than the HW cotton and other leaves are lighter colored due to water stress and varying stages of senescence. The width of the LW cotton canopy is narrower than that of the HW cotton canopy and the soil surface is visible in a few areas within the canopy boundary. The HW corn canopy contains sunlit, narrow elongated leaves and a high proportion of shaded area. Corn tassels are also visible and the top surface of the canopy appears less uniform than cotton.

The thermal images have lower resolution than the color photos and provide less detail about the canopy architectural differences between the two crops. The variations in greyness do provide a visual estimate of the relative variations in temperature observed by viewing the canopies from above. Contrasting the two cotton canopies, HW cotton is darker grey and more uniform in greyness than the LW cotton canopy which has a wider range of greyness including light areas that indicate higher temperatures. The general greyness level of the HW corn canopy is similar to the HW cotton. There are a few light areas in the corn image which maybe sections of sunlit leaves that have elevated temperature. The patterns and shapes within the three canopy thermal images are due to spatial temperature distributions, leaf shapes, and shaded areas.

The information contained in the color photos and thermal images emphasizes the complexities of crop canopy surfaces and the range of surface variations present in different crops and physiological conditions. The temperature of a canopy measured by a remote thermal sensor is an integrated average of the area viewed and in reality is a composite value of all canopy components in the field-of-view. The measured canopy temperature is not that of a uniform two dimensional surface but is a multi-dimensional surface due to irregularities and holes in the upper surface and to orientation and shape of individual elements.

Table 4
Frequency distribution of canopy temperatures for cotton and corn for each day during one irrigation cycle, 2001

Temperature range (°C)	HW cotton (%)	LW cotton (%)	Corn (%)	Temperature range (°C)	HW cotton (%)	LW cotton (%)	Corn (%)
	DOY 199				DOY 200		
28–30	0.67	–[a]	–	28–30	15.80	–	–
30–32	35.13	–	9.62	30–32	72.41	–	11.82
32–34	53.06	24.06	86.36	32–34	10.85	–	77.90
34–36	9.50	59.97	3.77	34–36	0.75	0.25	9.82
36–38	1.26	13.41	0.11	36–38	0.19	33.14	0.36
38–40	0.39	2.25	0.04	38–40	–	54.03	0.09
40–42	–	0.28	–	40–42	–	11.86	–
42–44	–	–	–	42–44	–	0.72	–
44–46	–	–	–	44–46	–	–	–
46–48	–	–	–	46–48	–	–	–
Mean	32.5	34.9	32.8		30.9	38.6	32.9
S.D.	1.4	1.4	0.7		1.1	1.3	0.9
CV (%)	4.3	4.0	2.3		3.6	3.5	2.8
Uniformity[b]	88	84	96		88	87	88
	DOY 201				DOY 202		
28–30	–	–	–	28–30	–	–	–
30–32	–	–	0.73	30–32	1.20	–	0.41
32–34	–	–	46.13	32–34	60.64	–	64.60
34–36	72.88	–	49.63	34–36	35.45	–	34.23
36–38	23.85	2.43	3.24	36–38	2.63	3.14	0.69
38–40	2.32	46.45	0.27	38–40	0.25	26.71	0.06
40–42	0.70	38.79	–	40–42	0.01	43.35	–
42–44	0.25	10.38	–	42–44	–	22.31	–
44–46	0.01	1.94	–	44–46	–	4.49	–
46–48	–	0.02	–	46–48	–	–	–
Mean	35.6	40.3	34.1		33.8	41.0	33.8
S.D.	1.5	1.6	1.1		1.8	1.8	0.8
CV (%)	4.1	3.9	3.3		5.4	4.3	2.2
Uniformity	97	85	96		96	70	99

[a] Indicates that the percent value is zero.

[b] Uniformity is the summed percentage of temperatures contained in the two highest adjacent temperature intervals.

3.6. Thermal imaging

The thermal maps developed from the TS data provided detailed information about the spatial and magnitude distribution of canopy temperature (Table 4). Irrigation was applied on DOY 199 before temperature measurements were initiated. The distribution of canopy temperature values was more uniform for the well-watered HW cotton and corn than the water-stressed LW cotton canopy. Standard deviation and coefficient of variability values indicated that HW corn canopy temperatures had less variation than both cotton water levels on all days during the irrigation cycle. Uniformity of temperature was computed as the sum of percentages in the two adjacent temperature intervals having the largest individual values. On all days during the irrigation cycle, the quantity of total temperatures included in the two highest adjacent temperature intervals of HW cotton and HW corn was equal to or greater than in LW cotton. The distribution of LW cotton canopy temperature was most similar to the well watered crops on DOY 199 and DOY 200 and then its range of temperatures increased in relation to the well-watered crops on the last two days of the irrigation cycle. The individual 2 °C temperature interval areas in the thermal maps of the two water levels of cotton and corn did not indicate any unique patterns, except for the size of areas for the temperatures of the highest adjacent intervals which determined the uniformity value.

4. Conclusions

Infrared thermometer and thermal scanner sensors measured similar canopy temperatures in HW cotton and HW corn because their difference was less than the measurement precision of the two sensors. The IT measured higher average canopy temperature than TS in LW cotton (3.2 °C) which was likely caused by more soil being viewed within the canopy perimeter by the IT than the TS. Canopy temperature measured by both sensors had a high degree of 1:1 linear correspondence in HW cotton and HW corn over a temperature range from 30 to 40 °C. Frequency distribution analysis of thermal scanned canopy temperatures indicated that corn canopy surface temperatures had lower variability than cotton. When canopy size is sufficient to mask the soil background, canopy temperatures measured from a small area by infrared thermocouples were comparable to those from a larger area viewed by a thermal scanner. Measurements of relatively small fixed areas of a crop canopy with an IT can provide sufficiently accurate temperatures to characterize crop water stress and manage the timing of irrigation applications.

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